Atmospheric Environment 184 (2018) 1–8

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

# Emission characteristics of NOx, CO, $NH_3$ and VOCs from gas-fired industrial boilers based on field measurements in Beijing city, China

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ARTICLE INFO

*Keywords:*
Gas-fired industrial boilers
Gaseous pollutants
Emission inventory
Operating load
Flue gas recirculation

ABSTRACT

In the past decade, due to the management policies and coal combustion controls in Beijing, the consumption of natural gas has increased gradually. Nevertheless, the research on the emission characteristics of gaseous pollutants emitted from gas-fired industrial boilers, especially considering the influence of low nitrogen (low-NOx) retrofit policy of gas boilers, is scarcely. In this study, based on literature and field investigations, onsite measurements of NOx, CO, $NH_3$ and VOCs (Volatile Organic Compounds) emissions from gas-fired industrial boilers as well as the key factors that affected the emission of gaseous pollutants were discussed. Category-specific emission factors (EFs) of NOx, CO, $NH_3$ and VOCs were obtained from the field measurements of 1107 "low-NOx" retrofitted and unabated gas-fired industrial boilers. Our results showed that operating load and control measures were the two key factors affecting the formation of gaseous pollutants. The EFs of NOx ($EF_{NOx}$) and CO ($EF_{CO}$) of atmospheric combustion boilers (ACBs) were much higher than the EFs of chamber combustion boilers (CCBs). The total emissions of NOx, CO, $NH_3$ and VOCs from gas-fired industrial boilers in Beijing in the year of 2015 were estimated at 10489.6 t, 3272.8 t, 196.4 t and 235.4 t, respectively. Alkanes, BTEX, oxygenated VOCs and non-reactive organic matter were the four main chemical components of VOCs. As for the spatial distributions, the emissions of NOx, CO, $NH_3$ and VOCs from gas-fired industrial boilers in Beijing were predominantly concentrated in central six urban districts. In the future, more detailed investigation and field tests for all kinds of gas-fired industrial boilers are still greatly needed to achieve more reliable estimations of atmospheric pollutants from gas-fired industrial boilers.

## 1. Introduction

Nowadays, with the rapid development of economy and an increase in primary energy consumption, Beijing is facing severe environmental air pollution (Xue et al., 2016; Gao et al., 2018). Government has committed to control air pollution and improve ambient air quality by adjusting energy structure in recent years. With the implementation of the Clean Air Action Plan of Beijing 2013–2017, the energy structure of Beijing is continuously optimized. The application fields of natural gas are increasingly expanding so as to the gas consumption increases rapidly. In 2015, according to the gas development and planning from the Beijing Gas Group Co. Ltd, the consumption of natural gas increased from 6.1 billion $m^3$ in 2008 to 14.6 billion $m^3$, and more than 78% of natural gas was used for heating and power generation (BMCCM, 2017). In addition, the capacity and amount of gas-fired industrial boilers both accounted for more than 85% of the total industrial boilers (Xue et al., 2017).

Compared to coal, the particulate matter (PM) and $SO_2$ emissions from natural gas combustion are less. However, NOx is considered to be the most significant gaseous pollutant emitted from natural gas combustion (Simmons and Seakins, 2012; Zhang et al., 2016). NO and $NO_2$ are the main components produced from gas combustion. When NO and $NO_2$ are discharged into the atmosphere, nitric acid fog and nitrate are generated through a series of physicochemical reactions. Under sunlight, nitrate combines with hydrocarbons and ozone to produce photochemical smog, which has a great impact on the atmospheric environment and human health (Wu et al., 2010; Li et al., 2015; Feng et al., 2016). In 2016, the gas used in heating accounted for more than 30% in Beijing, and the gas-fired industrial boiler has been an important stationary source of NOx emission in Beijing (Yan et al., 2017). Nevertheless, the understanding of the emission characteristics of gas-fired industrial boiler is limited. Considering the emission

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https://doi.org/10.1016/j.atmosenv.2018.04.022
Received 2 February 2018; Received in revised form 11 April 2018; Accepted 13 April 2018
Available online 17 April 2018
1352-2310/ 

characteristics of gas-fired boiler, some studies have mainly focused on the NOx emission based on the field measurements (England et al., 2001; Pulles and Heslinga, 2004; Wang et al., 2016; Xue et al., 2017). Wang et al. (2016) presented the status of NOx emissions of district central heating gas boilers in Beijing by measuring eighty-five gas boilers. Xue et al. (2017) established a NOx emission inventory in Beijing based on the field measurements of five gas-fired industrial boilers. However, limited largely and systematically field measured data have been obtained to study the category-specific emission factors (EFs) of NOx, CO, $NH_3$ and VOCs for different types of gas-fired industrial boilers, which is essential for the estimation of accurate emissions and spatial variation of gaseous pollutants from gas-fired industrial boiler.

Furthermore, according to the revised Emission Standard of Air Pollutants for Boilers in Beijing (BMEPB, 2015), the NOx emission of the new built boilers must be lower than 30 mg/$m^3$ since April 1, 2017. Simultaneously, for the retrofitted boilers, the emission standard of NOx has dropped from 150 mg/$m^3$ to 80 mg/$m^3$. In order to ensure the implementation of this revised standard and encourage the low nitrogen (low-NOx) retrofit of existing gas (oil) boilers, Beijing municipal government proposed a Regulation of the Beijing Municipal Reward Replaces Subsidy for the Gas (oil) Boiler Low-NOx Retrofit in June 4, 2016 (BMEPB, 2016). Although there are no emissions standards of CO, $NH_3$ and VOCs for boilers at present, $NH_3$ and VOCs are the precursor of $PM_{2.5}$ secondary transformation. Additionally, CO, $NH_3$ and VOCs are the essential gaseous pollutants that should be considered in the ambient air quality model. Thus, with the increase in the number and capacity of gas-fired industrial boilers, the emission of CO, $NH_3$ and VOCs should be pay more attention.

However, seldom studies have been focused on the changes of the emission characteristics after the implementation of revised emission standard and relevant administration policies for the low-NOx retrofit of gas-fired industrial boilers. In the present study, we focused on investigating the emission characteristics of NOx, CO, $NH_3$ and VOCs emitted before and after the implementation of low nitrogen reforming policy of gas-fired boilers. The key factor that affected the emission of gaseous pollutants were also discussed. Category-specific EFs of NOx, CO, $NH_3$ and VOCs were obtained based on field measurements for 1107 low-NOx retrofitted and unabated gas-fired industrial boilers. The high spatial resolution of gaseous pollutant emission inventories (3 km × 3 km) were established and analyzed based on detailed information from gas-fired industrial boilers, including boiler position, boiler type, operating load, combustion mode, installed capacity, etc. Monte Carlo simulation was applied to calculate the uncertainty.

## 2. Data and methods

### 2.1. Study domain

Beijing, the capital city of China, is located in the Northern part of the North China Plain (39°54′ N, 116°23′E) covered a total area of 16,410.54 $km^2$ with 16 administrative districts. It is surrounded by the Taihang and Yanshan Mountains to the west, north and northeast. As the center of politics and culture of China, the population has already exceeded 21.7 million in 2016 (BMBS, 2016). With the rapid economic development, population expansion and urbanization, Beijing has experienced an ever-increasing energy consumption and the sharp increase of emissions of massive pollutants to the environment. In order to mitigate air pollution and improve air quality, Beijing municipal government has adopted numerous measures to reduce atmospheric pollutants emissions in recent years (He et al., 2014; Xue et al., 2016). In 2016, Beijing municipal government encouraged natural gas-fired industrial boilers to achieve low NOx combustion by equipping low NOx burners (LNBs) or post-combustion abatement techniques.

### 2.2. Activity data

The natural gas consumption was obtained from the China Statistical Yearbook (NBSPRC, 2016), Beijing Statistical Yearbook (BMBS, 2016) and other related references (Xue et al., 2017; Yan et al., 2017). A database containing detailed information of 12266 gas-fired industrial boilers with a gross capacity of 39705 t/h was established at the unit level. The detailed information included the geographic location, operating load, combustion mode, installed capacity, annual natural gas consumption, control technologies and pollutants concentration in the flue gas for each unit. Therein, combustion mode covered atmospheric combustion (AC) and chamber combustion (CC), and CC was subdivided into direct-combustion machine (CCM), horizontal internal-combustion (HIC) and others. Moreover, the majority capacity of the gas-fired industrial boilers is below 10 t/h, which account for more than 90% of the total amount. In terms of combustion mode, more than 80% of gas-fired industrial boilers is CC mode. The gas-fired industrial boilers in this database accounted for 77.5% of the total gas-fired industrial boilers in Beijing, which could be well represent the status of gas-fired industrial boilers in Beijing.

The geographic locations of gas-fired industrial boilers are presented in Fig. 1. As can be seen that gas-fired industrial boilers are mainly distributed in central six urban districts, namely Chaoyang, Dongcheng, Fengtai, Haidian, Shijingshan, and Xicheng district. It is related to the substitution of coal-fired boilers with gas-fired industrial boilers in urban district. Gas-fired industrial boilers are mainly used for heating and living in Beijing central urban district due to the high population density (Yan et al., 2017).

### 2.3. Field measurements

To investigate the actual EFs of gaseous pollutants (NOx, CO, $NH_3$, VOCs) from gas-fired industrial boiler, 1107 boilers were tested and analyzed (Table 1). It included 862 unabated gas-fired industrial boilers and 245 gas-fired industrial boilers with low NOx combustion techniques. Among these of 862 unabated gas-fired industrial boilers, there were 281 AC boilers and 581 CC boilers. While CC boilers accounted for the majority part of the 245 gas-fired industrial boilers. In the field measurements, operating load were controlled to above 75% to reflect the real emission level of gaseous pollutants emitted from gas-fired industrial boilers (Yan et al., 2017).

To clarify the influence of operating load and control measures on gaseous pollutants emission (NOx, CO, $SO_2$), the gaseous pollutants

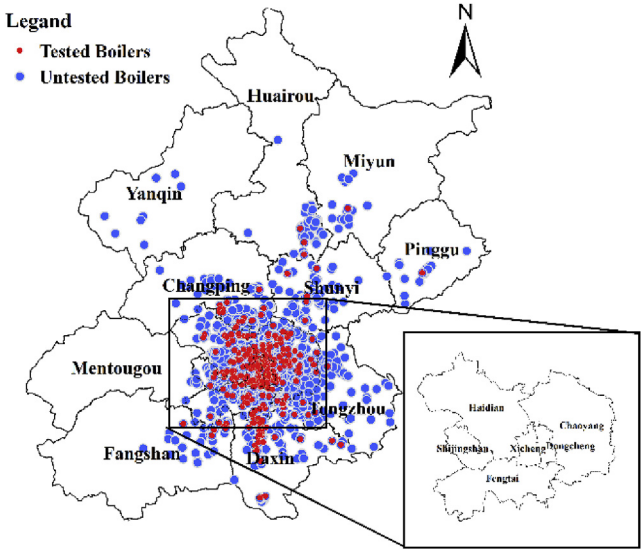


**Fig. 1.** Geographical locations of gas-fired industrial boilers in Beijing.